# A STUDY OF APPLICATION OF REMOTE SENSING TO RIVER FORECASTING

IBM No. 75W-00056

FINAL REPORT

VOLUME I – EXECUTIVE SUMMARY

(NASA-CR-143858) A STUDY OF APPLICATION OF REMOTE SENSING TO RIVER FORECASTING. VOLUME 1: EXECUTIVE SUMMARY Final Report (International Business Machines Corp.) 23 p HC $3.25 CSCL 08H G3/43

N75-25264

Unclas

24704

# PREFACE

The study whose results are reported in these volumes addressed a practical application of a technique whose feasibility had previously been determined, as reported in "Application of Remote Sensing to Hydrology, Final Technical Report" (NASA-CR-120278, NTIS Accession Number N74-27811). For economy, very little of the information contained in that previous report has been duplicated in this one. The reader is assumed either to be familiar with the basic concepts (the hydrologic cycle, hydrologic models, etc.) or to have access to the previous report.

Volume I of this report is a summary of technical results.

Volume II -- Detailed Technical Report: NASA-IBM Streamflow Forecast Model User's Guide -- describes the computer programs used in the study, with source listings, flow charts, and implementation instructions.

Note on use of the International System (SI) of Units: To the maximum practicable extent, quantities used in this report have been expressed in SI units, followed parenthetically by the equivalent English units. However, the use of English units is so pervasive in the model and its normal outputs (particularly the tabular ones) that complete conversion for this report would not have been practicable.

TABLE OF CONTENTS

# SECTION 1

# INTRODUCTION

## 1.1 OBJECTIVES

The primary objective of the study was to define, implement and evaluate a pilot demonstration test to show the practicability of applying remotely sensed data to operational river forecasting in gaged or previously ungaged watersheds. (Feasibility of the application had been shown in a previous study.) A secondary objective was to provide NASA with documentation describing the computer programs that comprise the streamflow forecasting simulation model used in the study.

## 1.2 SUMMARY OF RESULTS

A computer-based simulation model was adapted to a streamflow forecasting application and implemented in an IBM System/360 Model 44 computer, operating in a dedicated mode, with operator interactive control through a Model 2250 keyboard/graphic CRT terminal. The test site whose hydrologic behavior was simulated is a small basin (365 square kilometers) designated "Town Creek near Geraldine, Alabama." This watershed had been modeled in previous studies, and determination of several of its parameters through remote sensing had been found feasible. Operation of the model was demonstrated, as described in Section 3 below, in February 1975, meeting the primary study objective.

A description of the NASA-IBM streamflow forecast model, adequate to instruct another user in its operation, appears in Volume II of this report, in satisfaction of the secondary study objective.

## 1.3 CONCLUSIONS

### 1.3.1 APPLICABILITY OF REMOTE SENSING

There are basically two classes of inputs to the hydrologic model (which is the heart of the forecasting system). One of these classes consists of the operating parameters that must be quantified to tailor the model to a particular basin. The parameters are related to basin physical characteristics (though for many of them the relationship is not well known) that change slowly, usually over a period of years. The other class of inputs consists of the temporal data: precipitation, temperature (if the snowmelt routine is used) and evaporation, all of which change rapidly.

At present, remote sensing can practicably be applied to quantifying or estimating some of the model parameters and for updating them as basin characteristics change (by urbanization, for example). For those parameters that cannot be obtained readily by remote sensing, it is feasible to quantify them by statistical correlation with observable characteristics, but the technique needs further refinement

(see "Application of Remote Sensing to Hydrology, Final Technical Report," NASA-CR-120278, September 1973). The normal method of quantifying these parameters is by calibration based on several years of historical data.

The temporal inputs are not presently accessible through remote sensing, unless data relayed by satellite from data collection platforms is considered to be remotely sensed. Research and development programs aimed at remote sensing of temporal data are in process, but none useful to the river forecasting system have yet matured. When they are operational, they will be of more value to the data acquisition aspect of the system than to the modeling and simulation.

There are several moisture storage accounts maintained from hour to hour and day to day by the model itself. Examples are upper zone storage (approximating surface moisture, including vegetative interception) and lower zone storage (approximating soil moisture near the surface). If methods could be found to quantify these values on a daily basis, directly or by inference from remote sensing, and modify the model to accept the remote-sensed values as inputs, then simulation (or forecast) accuracy could be improved to within five percent.

### 1.3.2 DEVELOPMENT STATUS OF THE APPLICATION

The streamflow forecast model as used in the study is essentially a prototype. There are several operating features and capabilities that should be implemented in an operational system but which are not present in the prototype system. These differences, which do not detract from the validity of study results, are summarized in paragraph 2.1. The development status of the model is such that it could be brought to operational status in a short time by a user agency with minimal NASA advice or assistance.

## 1.4 SUMMARY OF RECOMMENDATIONS

In the application of remote sensing to river forecasting, the principal development areas are (1) the simulation models themselves and (2) techniques and sensing systems for extracting model inputs directly and indirectly from remotely sensed data. In the first area, with respect to currently conventional models, further developments and refinements should be left to users, while NASA continues to concentrate in the second area. (The image analysis and classification work being done by MSFC comes readily to mind.) In addition to monitoring these developments for improved applicability to hydrologic modeling (see Section 4), two near-term projects of limited scope are recommended by the study team:

- A cooperative study between NASA and one or more user agencies to review the results of this study and evaluate their applicability to each user's own operational needs
- A preliminary study of the feasibility of modifying an existing hydrologic model or developing a new one to accept remotely sensed inputs more directly.

## SECTION 2

## METHODOLOGY

The study consisted of the tasks described in the following paragraphs.

### 2.1 SYSTEM PERFORMANCE

At the beginning of the study, the desired capabilities, functions and features of the demonstration system were identified. This task was aided considerably by technical liaison with government organizations involved in development and operation of river forecasting systems: the River Control Branch of the Tennessee Valley Authority, the Hydrologic Research Laboratory and the Lower Mississippi River Forecast Center of the National Weather Service. The study team acknowledges the value of their advice and experience without imputing to them any endorsement of the study or its results.

#### 2.1.1 GENERAL PERFORMANCE OBJECTIVES

The system features and capabilities as design objectives were as follows:

- Applicability to small (less than 1,000 square kilometers in area) and large, or regional, watersheds
- Capability of future extension to apply to major river systems
- Capability of including snowfall and snowmelt in calibration and simulation programs
- Watershed model parameter estimation based on remotely sensed data and/or multi-year historical data
- Choice of multi-year, open-loop simulation (i.e., without initialization to observed streamflow for calibration purposes), or short-term closed-loop simulation (i.e., with initialization to observed streamflow) for operational forecasting
- Preprocessing of input data for calculation of mean basin temperatures, mean basin precipitation and potential evapotranspiration
- Remote terminal operation for batch processing job entry or interactive operation, depending on the capability afforded by the host computer system
- Choice of length of forecast period from one (1) to fourteen (14) days
- Generation of forecasts based on three kinds of precipitation inputs for the forecast period: zero (no precipitation), a quantitative forecast and worst-case forecast.

In general, the system should be the prototype of one with which an operator can do the following each day: (1) update the data base with the previous day's data (streamflow, precipitation, temperature and evaporation); (2) perform a "fine tune" run to match simulated (forecast) streamflow with actual streamflow at the beginning of the forecast period; (3) make forecasts of streamflow (period of one to fourteen days) based on the zero, quantitative and worst-case precipitation inputs.

### 2.1.2 DATA BASE

The data base consists of all the model parameters, control options and historical data needed to operate the system, as follows:

- o The "permanent" inputs are primarily the parameters needed to personalize the simulation/forecast model to the basin whose output streamflow is to be forecast. These parameters are determined from the best data sources available: field surveys, topographic maps, remote sensing, or calibration from historical data (see the final report previously referred to).

- o The historical inputs are actual:

  - hourly streamflow, in volume per unit time

  - hourly mean basin precipitation, synthesized from reports from all pertinent daily and hourly precipitation stations

  - daily evaporation rates, if available

  - maximum and mean basin temperature for each day, synthesized from reports from all pertinent temperature stations (applies only when snow accumulation is significant.)

- o Control options and other parameters needed for operation of the system

- o An array of moisture storages as calculated and maintained by the model. These variables--lower zone storage, upper zone storage, etc., constitute the initial conditions for the start of each forecast.

### 2.1.3 COMPUTER PROGRAMS

The system requires computer programs for:

- o Preprocessing input data

  - calculation of mean basin temperature from diverse temperature inputs

  - calculations of mean basin hourly precipitation from diverse precipitation station records

- reformatting temporal data from NWS climatological records and USGS streamflow records

- Calibration of the simulation/forecast model

- Performing simulation and forecast runs

- Interfacing with the host computer's operating system and peripheral-management software

- Analyzing, formatting and displaying results.

## 2.2 SYSTEM INTEGRATION

Most of the elements (hardware, software and manual techniques) were available with no modification to synthesize a system meeting the stated performance objectives. The significant exceptions were (1) some simulation model program modifications to provide variable-term forecast and simulation operations and (2) program additions to operate the forecast model in a user-oriented, interactive mode through a keyboard/graphics terminal.

### 2.2.1 TEST WATERSHED SELECTION

The watershed designated "Town Creek near Geraldine, Alabama," was one of a number studied by IBM under a previous NASA contract. Six years of usable historical data had previously been collected, using two hourly and five daily precipitation stations, and model calibration had been completed. The basin is representative of rural areas of moderate topography and temperate climate.

The basin is located in northeast Alabama, at the edge of the Tennessee River Valley, in the Cumberland Plateau physiographic region. Its area (see Figure 2-1) is 365 square kilometers (141 square miles), approximately sixty-five percent moderately forested and thirty-five percent cultivated. Impervious surfaces and water surfaces represent approximately 0.2 percent and 0.1 percent, respectively, of the entire watershed area. Surface soil is predominately sandy loam; the watershed is, in fact, located on top of what is known as "Sand Mountain." The stream channels are generally deep and steep sided, without well-defined flood plains; overflows have not occurred, even after the heaviest of recent precipitation events (e.g., March 1973).

Most accurate simulation was achieved using climatological data for water year 1964 (October 1963 through September 1964). A comparison of some single-year and long-term statistics is included in Figure 2-1. Although October was one of the driest months ever recorded, total precipitation for the year was only approximately eight percent greater than the long-term average. Some heavy rains occurred in March 1964 (approximately ten inches on March 25) but did not cause damage.

The ready availability of the relevant data made the Town Creek watershed attractive as a test site for the river forecasting application study, and it was so designated, with the concurrence of the COR.

| STATISTICAL DATA | | |
|---|---|---|
| STATISTIC | LONG TERM | 1964* |
| Average Discharge, $m^3/s$ | 8.04 | 9.20 |
| Peak Discharge, $m^3/s$ | 500.9 | 243.2 |
| Least Discharge, | 0 | 0 |
| Annual Precipitation, cm | 137 | 148 |

*Reference values used in sensitivity analysis

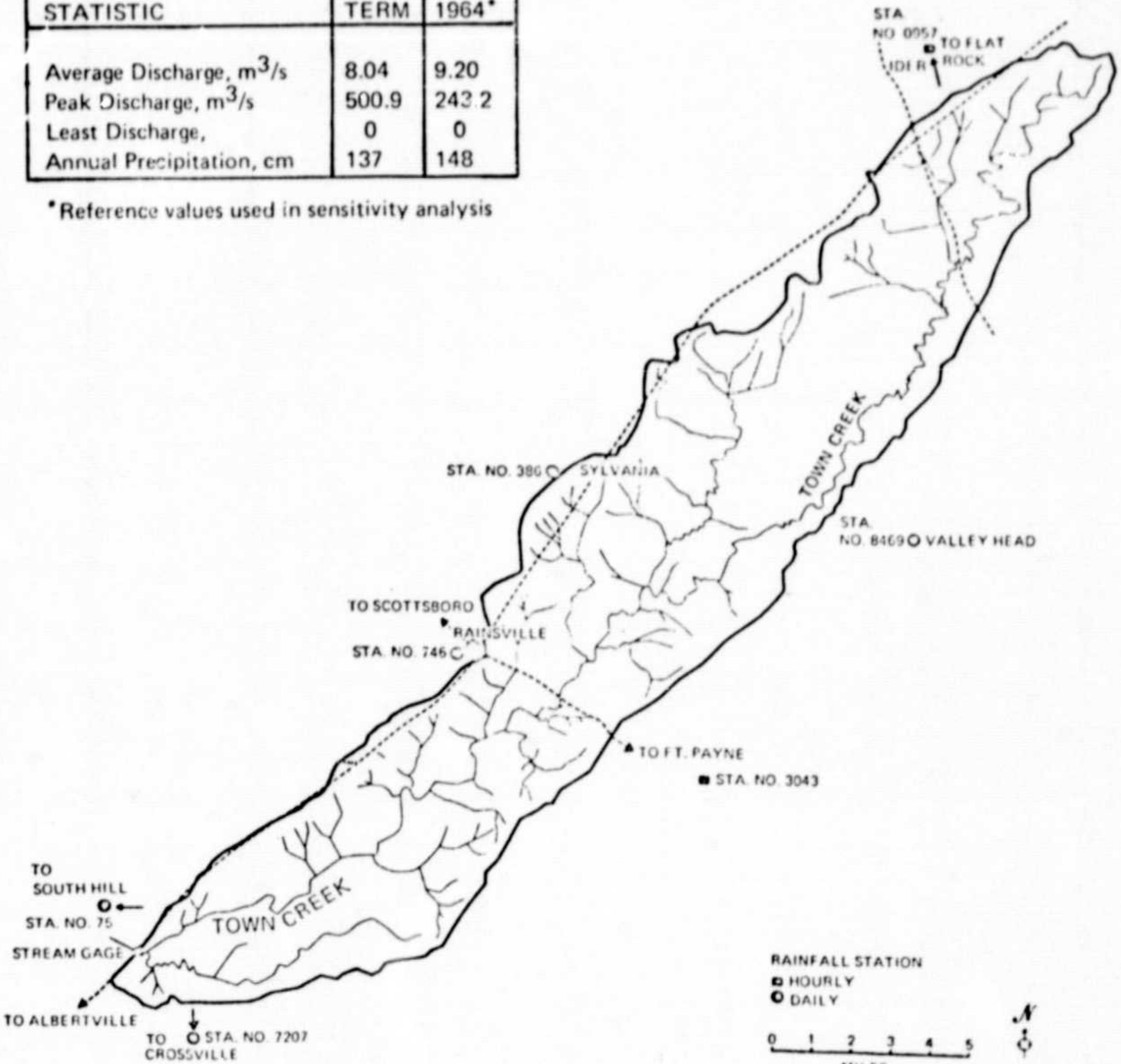




*Figure 2-1. Town Creek Watershed*

2.2.2 DATA BASE CONSTRUCTION

Adequate historical and physiographic data were already available for modeling the Town Creek watershed for pilot demonstration purposes. Some additional historical data applicable to a more recent period were also acquired. The validity of the data and calibration of the model were verified through a few simulation runs. The data base was placed in magnetic disk storage, using the water year 1964 as the year for which the forecasting application would be tested. The data base consists of the data listed in 2.1.2.

## 2.3 CALIBRATION

It is necessary to assign numerical values to the simulation model parameters to obtain acceptable simulation accuracy. The process of determining this best set of parameters is known as "calibration" or "optimization." This has previously been done for the Town Creek watershed model, and only a re-check of accuracy was required, based on a multi-year (1963-69) simulation.

The calibration performed previously was done in three steps. First, some of the model parameters were estimated from aerial photographs (directly, or indirectly through topographic maps) already available to the study team. These are the parameters, such as mean overland flow length (OFSL), related to basin physiography.

An optimization routine called OPSET (because it estimates the "OPtimum SET" of parameters; see Liou, 1970) was used to generate approximate parameter values that give acceptable simulation with respect to mean daily and monthly streamflow. A series of simulation runs were then made, simulated and actual storm events (peaks, timing of peaks and total runoff) compared, and certain parameters adjusted for acceptable storm-event simulations. Examples of parameter values are as follows:

- o Vegetative Interception Maximum Rate (VINTMR) = 3.8 mm/hr (0.15 inches/hour)
- o Basic Upper Zone Capacity (BUZC) = 0.08 mm (0.2 inches)
- o Seasonal Upper Zone Adjustment Constant (SUZC) = 0.20
- o Lower Zone Capacity (LZC) = 10.16 cm (4.0 inches)
- o Basic Maximum Infiltration Rate (BMIR) = 8.9 cm/hour (3.5 inches/hour).

## 2.4 IMPLEMENTATION

### 2.4.1 WATERSHED MODEL MODIFICATIONS

The NASA-IBM watershed simulation model required the following modifications to convert it to a streamflow forecast model.

- o Accumulation of initial soil moisture conditions on a daily basis
- o Initiation of a simulation run that starts before present time (a "past run" or "fine tune run"), using most recently observed streamflow and precipitation.
- o Input actual observed hydrograph data (hourly streamflow).
- o Manual adjustment of soil moisture parameters to fit simulated past-run hydrographs to observed hydrographs, in order to start each day's forecast run with simulated streamflow equal to observed streamflow.
- o Performing three simulations and superposing their output hydrographs, each having a different precipitation input, as follows:
  - Historic maximum precipitation (worst case)
  - Forecast quantitative precipitation
  - Zero forecast precipitation.

The principal difference between an operational model and the research simulation model is that the latter normally simulates one or more years of streamflow based on chronological input data, while the former is used to generate streamflow forecasts for periods of a few hours up to several days.

### 2.4.2 TERMINAL OPERATION

In order to be an effective forecasting tool, the simulation model was made accessible to the operator through a remote data entry and display terminal through which we could set up, select options and initiate the simulation runs. Software modifications were implemented to interface the terminal-management programs with the forecast model. The principal displays and options available are the following.

- o Tables of control options, parameters and initial conditions from which the operator can select modes of operation, modify parameters, and specify the forecast period
- o Tabular summaries of simulation results and forecasts
- o Superimposed plots of:
  - past-run simulated and observed streamflow for fine tuning, or
  - three streamflow forecast hydrographs.

Hard-copy printouts are also available from the system.

## 2.5 DEMONSTRATION

The prototype forecast model was operated several times, using periods in Water Year 1964 when there were storm events of interest, producing the results shown in Section 3.1.

## 2.6 DOCUMENTATION

The second volume of this report describes the computer programs used in the study, with source listings, flow charts and implementation instructions. The documentation is at a level appropriate to the research and developmental nature of the model but should be readily understood by an experienced system programmer.

## SECTION 3

## RESULTS

### 3.1 RIVER FORECAST MODEL OPERATION

Operation of the prototype river forecast model is illustrated, at a level suitable for this report, by the following sequence of operations.

At the beginning of the forecast period, the operator places the program in core and gains access to the data bank via the terminal. He selects a control option for "past run" and the beginning and ending dates (the latter being the day previous to the first day of the forecast period). The previous day's observed data (temperature, evaporation, mean hourly precipitation, and hourly streamflow) will have been placed in the master data bank. The result of the past run is a pair of hydrographs, such as those shown in Figure 3-1.

In this example, the two hydrographs do not match, the simulated streamflow being greater than the observed. The operator accesses the data bank again and makes some adjustments of initial soil-moisture values. The process (which would be done automatically in an operational system) is repeated as necessary to obtain an acceptable match. This depends mainly on operator experience. In the example chosen, Lower Zone Storage (LZS) was reduced from 3.3 cm (1.3 inches) to 2.34 cm (0.92 inches). This caused more simulated infiltration and less simulated runoff and produced a coincidence in the two hydrographs, as shown in Figure 3-2. The soil-moisture conditions at the end of the previous day (beginning of the forecast period) are then transferred to the data bank, which is now ready for a forecast run.

The inputs for the forecast run include temperature, evaporation and worst-case precipitation, which can be derived from weather statistics. If it is available or can be synthesized, a quantitative precipitation forecast is also used. A "zero" precipitation forecast is implemented in the program. The operator selects the forecast period (one to fourteen days) and initiates the run, the results of which appear much like those of Figure 3-3. Tabular outputs such as those of Table 3-1 are also available. The values of hourly streamflow (in cubic feet per second, cfs) apply at the stream gage (basin mouth) and with suitable rating tables (always available) can be readily converted to stream height.

### 3.2 APPLICABILITY OF REMOTE SENSING

It is presently feasible, using existing image data processing and analysis techniques, to quantify eight of the parameters involved in the simulation models from either LANDSAT or Skylab bulk - processed images. These parameters are: impervious fraction of basin area (FIMP), water surface fraction

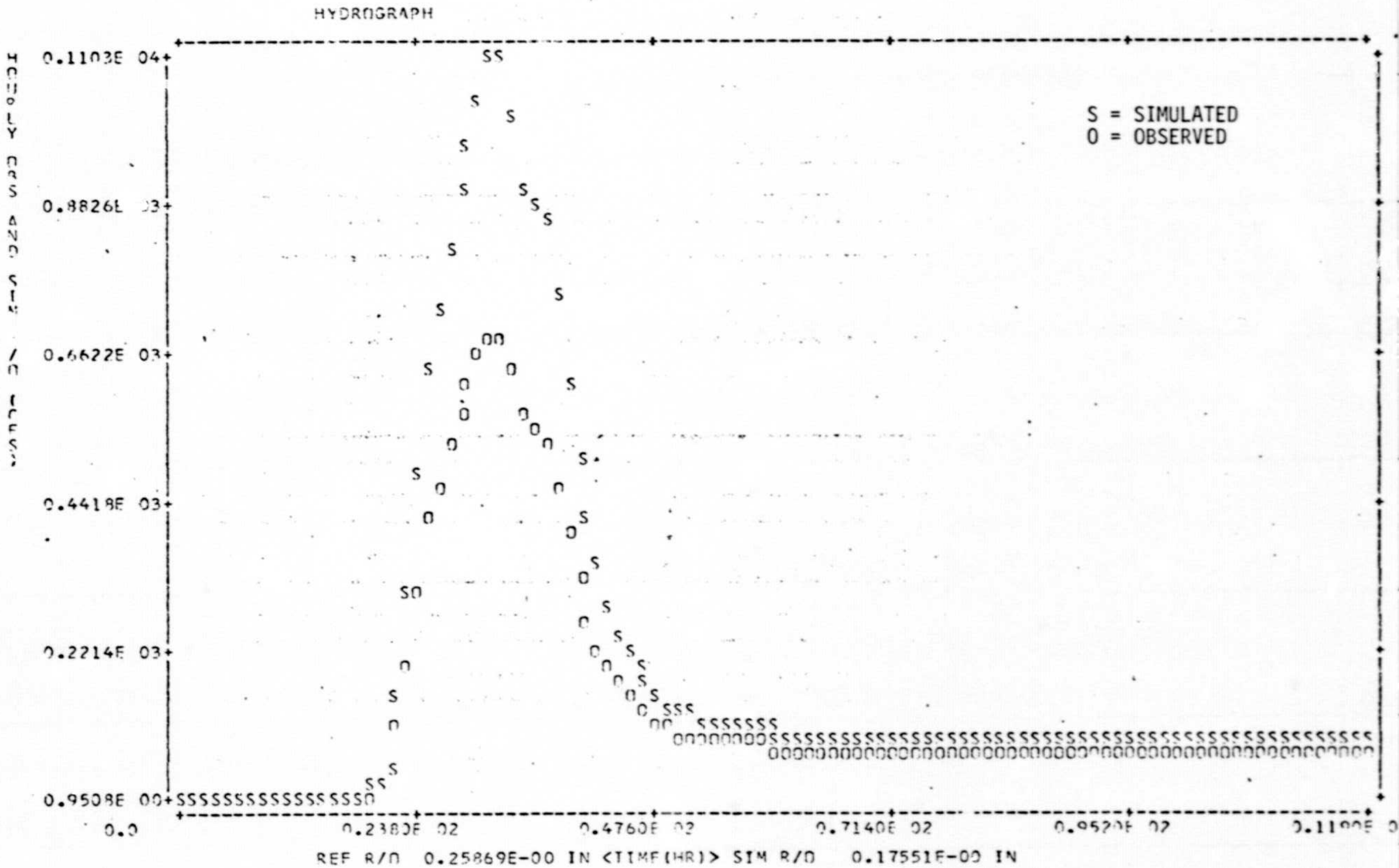


Figure 3-2. Example of Past Run Output Plot After Adjustment of Initial Conditions

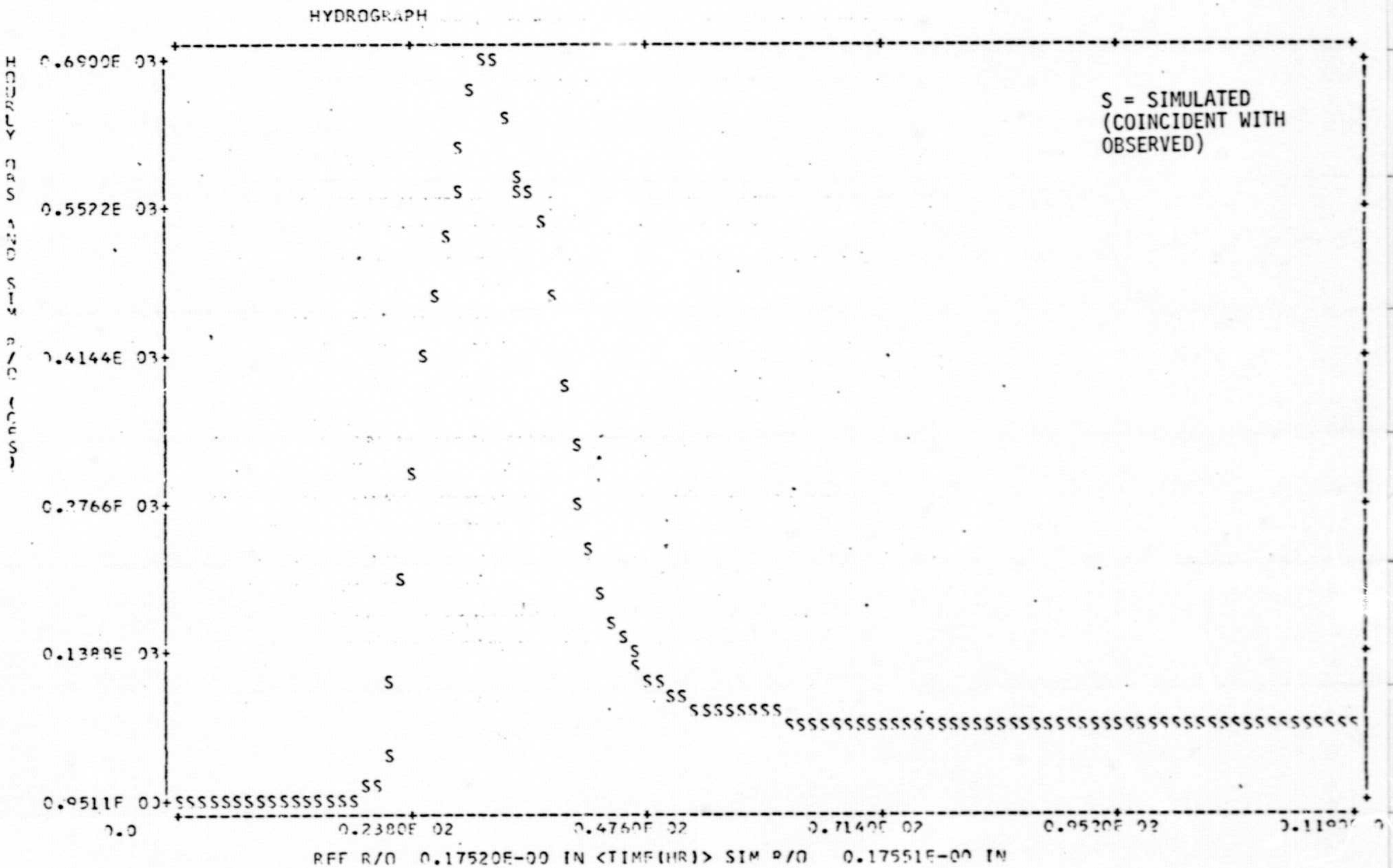


Figure 3-1. Example of Past Run Output Plot

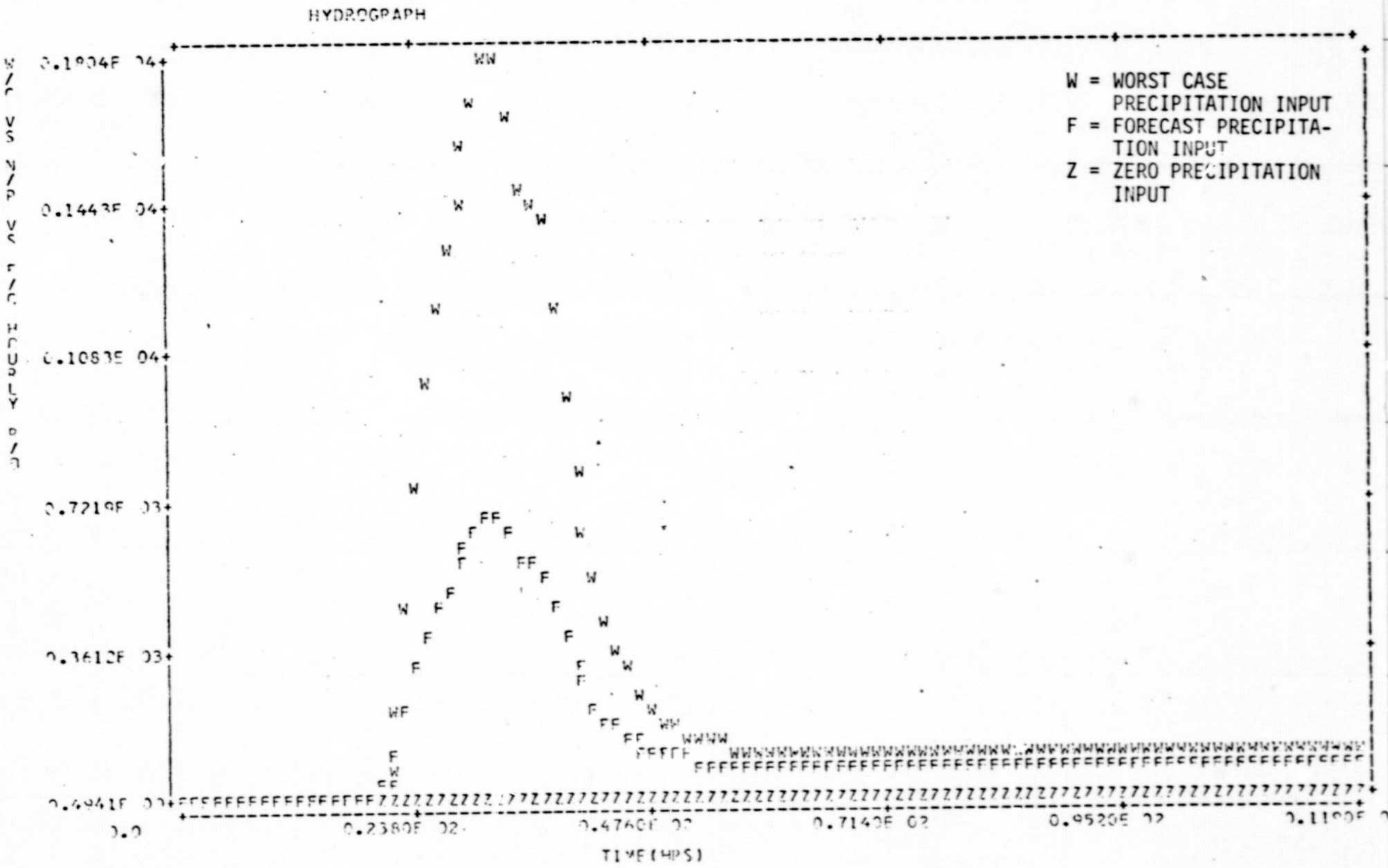


Figure 3-3. Example of Streamflow Forecast Plots

Table 3-1. Example of Tabular Forecast Output

TOWN CREEK

WORSE CASE HOURLY CFS VALUES

| NOV | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | AM | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 | |
| | PM | 1.0 | 1.0 | 1.1 | 1.9 | 3.3 | 6.1 | 10.4 | 15.1 | 26.3 | 62.9 | 228.4 | 480.1 | 35.5 |
| 5 | AM | 753.8 | 1027.0 | 1181.8 | 1329.0 | 1453.2 | 1584.5 | 1705.[illegible] | 1792.8 | 1803.2 | 1663.9 | 1499.5 | 1462.4 | |
| | PM | 1447.7 | 1399.6 | 1202.4 | 984.9 | 800.5 | 653.0 | 535.7 | 443.3 | 371.1 | 314.4 | 270.1 | 235.5 | 1079.0 |
| 6 | AM | 208.4 | 187.1 | 170.5 | 157.5 | 147.3 | 139.3 | 132.9 | 127.9 | 123.9 | 120.7 | 118.2 | 116.2 | |
| | PM | 114.6 | 113.3 | 112.2 | 111.4 | 110.6 | 109.9 | 109.4 | 108.9 | 108.6 | 108.1 | 107.8 | 107.4 | 128.0 |
| 7 | AM | 107.1 | 106.8 | 106.4 | 106.1 | 105.8 | 105.5 | 105.2 | 105.0 | 104.3 | 104.1 | 103.8 | 103.5 | |
| | PM | 103.3 | 103.0 | 102.7 | 102.5 | 102.2 | 101.9 | 101.6 | 101.3 | 101.4 | 101.1 | 100.8 | 100.5 | 103.6 |
| 8 | AM | 100.2 | 99.9 | 99.6 | 99.3 | 99.0 | 98.7 | 98.4 | 98.1 | 97.4 | 97.1 | 96.8 | 96.5 | |
| | PM | 96.2 | 95.9 | 95.6 | 95.4 | 95.1 | 94.8 | 94.5 | 94.2 | 94.4 | 94.1 | 93.8 | 93.5 | 96.6 |

FORECAST CASE HOURLY CFS VALUES

| NOV | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | AM | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 | |
| | PM | 1.0 | 1.0 | 1.0 | 1.4 | 2.4 | 4.4 | 7.6 | 11.0 | 18.8 | 41.3 | 109.9 | 205.7 | 17.5 |
| 5 | AM | 338.1 | 409.9 | 466.3 | 521.1 | 566.0 | 613.5 | 656.6 | 686.7 | 689.0 | 637.6 | 575.6 | 566.6 | |
| | PM | 559.8 | 537.5 | 468.8 | 391.0 | 325.2 | 272.4 | 230.2 | 197.0 | 171.1 | 150.6 | 134.6 | 122.1 | 427.4 |
| 6 | AM | 112.2 | 104.5 | 98.4 | 93.7 | 90.0 | 87.0 | 84.6 | 82.8 | 81.1 | 79.9 | 79.0 | 78.2 | |
| | PM | 77.5 | 77.0 | 76.6 | 76.2 | 75.9 | 75.5 | 75.2 | 75.0 | 74.9 | 74.7 | 74.4 | 74.2 | 82.4 |
| 7 | AM | 74.0 | 73.8 | 73.6 | 73.4 | 73.2 | 73.1 | 72.9 | 72.7 | 72.2 | 72.0 | 71.8 | 71.6 | |
| | PM | 71.4 | 71.3 | 71.1 | 70.9 | 70.7 | 70.5 | 70.3 | 70.1 | 70.3 | 70.1 | 69.9 | 69.7 | 71.7 |
| 8 | AM | 69.5 | 69.2 | 69.0 | 68.8 | 68.6 | 68.4 | 68.2 | 68.0 | 67.4 | 67.2 | 67.0 | 66.8 | |
| | PM | 66.6 | 66.4 | 66.2 | 66.0 | 65.8 | 65.6 | 65.4 | 65.2 | 65.5 | 65.3 | 65.1 | 64.9 | 66.0 |

NO PRECIP HOURLY CFS VALUES

| NOV | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | AM | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 | |
| | PM | 1.0 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.3 | 1.3 | 1.3 | 1.3 | 1.1 |
| 5 | AM | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.1 | 1.1 | 1.1 | 1.1 | |
| | PM | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| 6 | AM | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.0 | 1.0 | 1.0 | 1.0 | |
| | PM | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| 7 | AM | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 0.7 | 0.7 | 0.7 | 0.7 | |
| | PM | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 |
| 8 | AM | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.5 | 0.5 | 0.5 | 0.5 | |
| | PM | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 |

of basin area (FWTR), vegetative interception maximum rate (VINTMR), evapotranspiration loss factor (ETLF), mean overland flow surface length (OFSL), overland flow roughness coefficient (OFMN), fraction of watershed in forest (FFOR), and fraction of snow intercepted (FFSI).

Given successful development of image interpretation and analysis techniques presently in research and development, it may become feasible to quantify four additional parameters from remote-sensed image data of the same quality as that available from LANDSAT or Skylab. These parameters are: upper zone storage capacity (BUZC), upper zone capacity seasonal adjustment factor (SUZC), lower zone storage capacity (LZC), and basic maximum infiltration rate (BMIR).

In order to calculate basin area, it is necessary to determine the boundary of the watershed, which in turn is determined from basin topography and the location of the stream gage at the basin mounh. Knowledge of basin topography is also necessary to derivation of mean overland surface slope (OFSS) and the elevation difference between base thermometer and mean basin elevation (ELDIF). Such parameters are readily measured from stereo image pairs, something obtained from aerial photography but not at present from space. An attractive alternative technique would be to obtain topographic data from the output of a spaceborne laser altimeter, in several passes across the watershed. This would provide the information from which contour lines could be superimposed on the remotely sensed images. The vertical resolutions required for determination of these parameters is several times coarser than that which would be provided by a laser altimeter.

There are a large number of research and development activities in sensor technology and interpretation and analysis techniques which hold considerable promise for future applications and hydrologic modeling. New developments in radiometric sensing may eventually allow remote measurement of atmospheric temperature at earth or snowpack surface, snow surface albedo and thereby the fraction of incoming radiation reflected by snow (FIRR), snowpack water content and related snow parameters, and soil moisture. All these inputs should be measured and quantified on at least a daily basis. Other intermediate to far future potential applications include determination of subsurface phenomena and conditions, such as seasonal infiltration adjustment factor (SIAC). A potential alternative approach to this latter class of parameters is by statistical correlation with observable features, a question previously investigated by IBM (see Reference 1).

For the foreseeable future, direct measurements of precipitation, evaporation and such statistics as the mean number of rainy days (MNRD) will be done by instruments located in the field, perhaps reporting their readings through satellite relay.

There are two parameters which have no recognizable relationship to watershed geomorphology and which are not susceptible to any present of future remote sensing application. They are the basic degree day factor for snowmelt (BDDSM) and a snowpack basic maximum fraction in liquid water (SPBSLW). There are other parameters involved in watershed simulation modeling to which the same comment applies. Such parameters will always have to be estimated by the hydrologist or operator of the simulation model, either through empirical relationships, experience or model calibration, unless developments in watershed simulation models lead to ways in which such parameters can be dispensed with, a much more desirable approach.

Proven watershed simulation models have been designed and implemented to accept inputs known to be available from ground-based instrumentation systems, topographic maps, field surveys and empirical relationships. To take advantage of the potential benefits to be expected from remote sensing, a hydrologic simulation model should be designed or redesigned to accept inputs more directly related to the data outputs of remote observation systems. The model used in the study could, for example, be improved in accuracy by accepting a daily soil moisture reading as an input rather than calculating soil moisture internally.

The model used in the study has been found in previous studies to be particularly disappointing from a remote sensing application standpoint with respect to its management of moisture in the form of snow. Many of the parameters used internally and as inputs depend upon empirical relationships and the acquisition of statistics over a long period of time and careful calibration and adjustment generally based upon the knowledge and experience of a hydrologist. Only three of the snow parameters used in the study can be determined from remotely sensed data, either now or in the near future. Modifications will be required to enable the model to accept inputs from newly developed remote sensing systems and techniques when they become available.

# SECTION 4

## RECOMMENDATIONS

In studying and developing means of improving streamflow forecasting (in accuracy, efficiency or economy) through remote sensing, there are two areas of investigation. One of these concerns the hydrologic models themselves - their utility, acceptability to users and ability to accept inputs derived from remote sensing. The other, a much larger endeavor, includes the sensors, sensor systems and techniques for deriving model inputs from remotely acquired data. Within the context of this study and its predecessors, the two areas are mutually interdependent. The choice of hydrologic model determines the requirements on the sensors and information-extraction techniques. The practical limits on the latter constrain the design of the hydrologic model.

This study and its predecessor feasibility study used a continuous (or parametric) hydrologic simulation model that is a descendant of the well-known and widely used Stanford Watershed Model IV. Although it served only as a device for demonstration of study results, developments and improvements, to make it more user-oriented and cost-effective, were necessary for completion of both studies. The model, in its long-term simulation version and its short-term forecast version, is essentially a prototype, further development of which NASA need not sponsor directly. This is the job of the user, and in fact several similar models are in various stages of development (see, for example, reference 10). Nevertheless, remembering the interdependence between model design and remote sensing systems (considered end-to-end, from sensing instrument through processed information products), NASA should have a continuing role in maintaining communication between the two. The present state of applicability of remote sensing was summarized previously in 3.2. These considerations lead to the following recommendations.

There are several closely related topics which deserve continued intensive study. Some investigators are presently exploring some of these topics; such investigations should be closely monitored and supplemented as needed. Those of particular interest are as follows:

- Determination of soil association and classification as well as subsurface characteristics by inference from remotely observable characteristics such as land use and vegetative cover

- Remote measurement of temporal phenomena: precipitation, air temperature, relative humidity, evaporation rate

- Determination by remote observation of snowpack depth at sufficient points to calculate total snowpack volume and water equivalent

- o Remote measurement of soil moisture on a daily basis within the watersheds

- o Determination of surface topography from orbital attitudes by a laser altimeter or stereographic images.

A study should be conducted of the feasibility of developing a multiple application watershed model capable of accepting inputs and parameters directly or closely related to the outputs of remote sensing systems. This study should include a coarse trade-off between developing a new model or modifying an existing one. It is desirable to have one or more potential users, experienced in hydrology, participate actively in such a study.

The results of this study should be reviewed and evaluated by one or more non-NASA user agencies (e.g., Corps of Engineers, TVA, National Weather Service). Evaluation should include degree of potential values to the agency if pursued through additional development, what that additional development should consist of, what effect using a different basic model may have on the validity of the results, and an assessment of the applicability in other areas. A logical extension of such an evaluation would be implenentation of the model and a user's data bank at MSFC with the user operating the system for a short term for evaluation purposes.

## SECTION 5

## REFERENCES

This is not intended as an exhaustive bibliography. A lengthy bibliography, with abstracts, was provided the COR early in the study. All the references listed in this section have been provided or made available to the COR.


1. Ambaruch, R., and Simmons, J.W., "Application of Remote Sensing to Hydrology," Final Technical Report, IBM No. 73W-00387, September 1973, for NASA George C. Marshall Space Flight Center (NASA-CR-120278, NTIS N74-27811).

2. Crawford, N.H., and Linsley, R.K., Digital Simulation in Hydrology: Stanford Watershed Model IV, Stanford, California: Stanford University, Department of Civil Engineering, Technical Report No. 39, July, 1966.

3. Hydrocomp International, "HSP Operations Manual," Palo Alto, California, 1969.

4. Anderson, E.A., and Crawford, N.H., The Synthesis of Continuous Snowmelt Hydrographs on a Digital Computer, Stanford, California: Stanford University, Department of Civil Engineering, Technical Report No. 36, 1964.

5. James, L.D., An Evaluation of Relationships Between Streamflow Patterns and Watershed Characteristics through the Use of OPSET: A Self-Calibrating Version of the Stanford Watershed Model, Lexington: University of Kentucky, Water Resources Institute. Research Report No. 36, 1970.

6. Liou, E.Y., OPSET: Program for Computerized Selection of Watershed Parameter Values for the Stanford Watershed Model, Lexington: University of Kentucky Water Resources Institute, Research Report No. 34, 1970.

7. Ross, G.A., The Stanford Watershed Model: The Correlation of Parameter Values Selected by a Computerized Procedure with Measurable Physical Characteristics of the Watershed, Lexington: University of Kentucky Water Resources Institute, Research Report No. 35, 1970.

8. Linsley, Ray K., Kohler, Max A., and Paulhus, Joseph L.H., Hydrology for Engineers. New York: McGraw-Hill Book Company, 1958.

9. Striffler, W.D., User's Manual for the Colorado State University Version of the Kentucky Watershed Model, Colorado State University, published under NASA Contract NAS9-13142, September 1973.

10. Hydrology Research Laboratory, National Oceanic and Atmospheric Administration, National Weather Service, U.S. Department of Commerce, National Weather Service River Forecast System Forecast Procedures. NOAA TM NWS-HYDRO-14, Washington, D.C., December 1972.